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Modeling Chilling Requirement and Diurnal Temperature Differences on Flowering Time and Fruit Yield to Identify Best Harvest Date in Strawberry Crown Production

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Executive Summary

The key to developing an export market for Saskatchewan-grown strawberry crowns is to export consistently high crown quality. Crown quality is directly dependent upon the chilling requirement, however, current models cannot accurately assess when chilling requirement is satisfied so that harvest can occur. The commercial production of strawberry crowns needs a quantifiable method, or models, to accurately assess chilling requirement and predict when to harvest for optimal crown quality. Most modeling approaches describing chilling effects on strawberry flowering time and yield are based on data from controlled environments, which may not be representative of commercial production. This study used commercial field yield data accumulated over a six year period and several geographically distinct locations to construct the models. Accumulative chilling unit (ACU) was estimated using both simple and weighted accumulation models and was related to yield and flowering time. ACU represents the sum of the number of hours at the specified temperature multiplied by the numerical weighting for that temperature range over time. Simple models accumulated the total number of hours between a wide range of chilling temperatures to which plants were exposed. Weighted models applied a numerical weighted value to a series of narrow ranges of temperatures. In both simple and weighted models, the numbers were totalled to provide a numerical value which was then used in a regression analysis with either time to first flower or fruit yield response. The results showed that flowering time was well correlated with ACU using either a simple accumulation model or a weighted accumulation model. The best correlation of flowering time with ACU was a quadratic

function ($y=82.27-0.049x+1.74e^{-5}x^2$) with effective temperatures from -2 to 15°C. By contrast, fruit yield was correlated with a weighted accumulation model and the relation was influenced by both a model weighting system and effective or inhibitive temperatures involved in the model with Model 2 being significant (< -1°C were given a weighting of -1.0; ≥-1 ~ < 0°C were given a weighting of 0.8; ≥ 0 ~ < 2°C were given a weighting of 1.0; ≥2 ~ <5°C were given a weighting of 0.8; ≥ 5 ~ < 8°C were given a weighting of 0.4; ≥ 8 ~ < 15°C were given a weighting of 0.2; ≥ 15 ~ < 25°C were given a weighting of 0.0; ≥ 25°C were given a weighting of -1.0 chilling unit (°C).

Since fruit yield and time to first flower responded significantly to different models, chilling temperatures may have separate effects on fruit yield and flowering time. Yield can be best predicted by a quadratic function ($y = -72.15+0.98x+0.0022x^2$) of a weighted ACU starting from about 6 weeks before crown harvest. In addition, yield response to a weighted ACU had an optimal level over which yield was reduced. Fruit yield was linearly associated with diurnal temperature differences across years and locations such that the greater the diurnal temperature difference, the greater the early fruit yield. However, the flowering time was affected interactively by diurnal temperature difference and day length. There was also a higher variation in geographically separate locations. Based on data pooled from 1996 to 2003 (excluding 1997) from five locations, the greater the differences in diurnal temperature at 2 to 3 months before crown harvest, the higher the subsequent fruit yield and the shorter the flowering time.

The effect of temperature on flowering and fruit yield under controlled environment and greenhouse conditions was also tested. Maximal diurnal temperature difference weighting scores were assigned as: Max-Min temperature > 16°C: 2.5; > 14 ~ ≤ 16°C: 2.0; > 12 ~ ≤ 14°C: 1.5; > 10

~ ≤ 12°C: 1.0; > 8 ~ ≤ 10°C: 0.5; > 6 ~ ≤ 8°C: 0; > 4 ~ ≤ 6°C: -0.5; > 2 ~ ≤ 4°C: -1. These scores were totalled over 15, 30 and 45 days of exposure and provided an index of diurnal temperature difference. Consistent with field results, flowering time induced under controlled environments was best correlated with the simple ACU. Diurnal min./max temperatures of -5/19, -3/21 and -1/23°C respectively were more effective at inducing greater fruit yield than higher min./max. temperatures of +1/25 and +3/27°C.

In conclusion, the greater diurnal temperature difference at cooler temperature regimes may be the major contributor to the Northern Vigour® response of strawberry crowns produced in Saskatchewan. An accumulative diurnal day-night temperature index of 180 resulted in yield enhancements of 30% for Saskatchewan-grown crowns compared to California-sourced crowns. Since this response is linear, the day/night temperature differences can be placed into a model and a running total of accumulative day-night temperature indices can be monitored to determine optimum harvest date. A combination of accumulative day-night temperature index and application of a chilling model may most accurately predict fruit yield response and best time to harvest.

Additional index words. Accumulative chilling unit, diurnal temperature difference, early yield, flowering time, yield modeling, strawberry

Introduction

The production advantages of vegetatively propagated crops such as potatoes grown in northern latitudes compared to southern sources has long been known by potato growers in Europe and North America. Studies demonstrated that the relative vigour and yield potential of

seed potatoes produced in Saskatchewan were superior to those from the USA. Over a 7 year period, Canadian-sourced crowns out-performed California-sourced crowns in each year from at least one Canadian-sourced location (Tanino, 2002). Since the highest prices of marketable fruit occur in these first 2 months, early yield will be of advantage to California producers. This relative phenomenon has been termed 'Northern Vigour®'. The Northern Vigour® response in strawberries (*Fragaria* x *ananassa* Duch.) is clearly environmentally regulated. With the changing climate particularly over the past several years, not surprisingly, this response has also been variable which, in some years, resulted in poorer yields than the California-sourced crowns. Since the Northern Vigour® response is dependent upon the chilling requirement, knowledge of when the chilling requirement is satisfied is important. However, current models cannot accurately assess when chilling requirement is satisfied so that harvest can occur. Commercial producers of strawberry crown and fruit urgently need quantifiable methods to predict crown harvest date, crown quality, and yield increase potential with Northern Vigor®.

Modeling approaches that are based on physiological responses of plants to their environment have more potential to be successful than those relying strictly on abiotic factors (Forcella et al., 2000; Bradford, 2002). Strawberry physiological responses in vegetative growth, flowering and reproduction to chilling temperature have been extensively studied (Risser and Robert, 1993; Tehranifar et al., 1998; Darnell, 2003). In general, chilling temperature (0 to 7°C) promotes maximal vegetative growth and initiates inflorescences while high temperature (> 25°C) may inhibit flower induction (reviewed by Darnell, 2003). Conversely, a long chilling period may enhance vegetative growth at the expense of flowering (Avigdori-Avidov et al., 1977; Lieten et al., 1995; Lieten, 1997). Floral initiation may also be induced by complex interactions

of temperature and photoperiod or day length (Durner and Poling, 1988; Okimura and Igarashi, 1997; Hytonen et al., 2004). Existing models developed for other crops commonly use weighted accumulation of chilling hours to describe the chilling requirement or temperature effects on flower initiation (Fulton et al., 2001; Dale et al., 2003). Although the weight of each temperature range used for chilling hour accumulation and modelling is estimated empirically, it should reflect the temperature dependence of physiological response rates. However, the weighted models are not widely applied in strawberry.

Fruit yield capacity of strawberry may be influenced by more complex environmental factors. Effects of temperature, including chilling on yield can be affected indirectly by flowering time, carbohydrate reserve and vegetation growth vigor. The optimum chilling temperatures are different for vegetative development and fruit productivity and quality in strawberry (Lieten, 2004). In addition, yield performance may associate with photoperiod (Hytonen et al., 2004), vegetative and reproductive growth competition and production management. Therefore, models that describe fruit yield and its relation to accumulative chilling unit (ACU) and temperature effects may be different from flowering time models.

The objectives of this study are to develop models that quantify the effects of chilling temperatures and diurnal temperature differences on strawberry flowering time and fruit yield. The developed models, based on field data from commercial fruit producers across different years and locations, are designed to predict crown harvest date and crown quality in strawberry plant production. The standard model with a simple accumulation of chilling hours was compared to our models with a weighted accumulation.

Materials and Methods

Experimental sites and yield data. Strawberry (*Fragaria* x *ananassa* Duch. cv. 'Camarosa') crowns were produced in northern regions of Saskatchewan and Alberta (Table 1). 'Camarosa' is a June-bearing cultivar, chosen for its early, high-yielding capabilities and wide acceptance within the California market. Saskatchewan-grown strawberry crowns were planted in late May or early June and were harvested in late September or early October and shipped to Oxnard, California (34°12'N 119° 00' W) where they were immediately planted. Flowering and fruiting subsequently occur in November and December, respectively with the first fruit harvest in the first week of December. The productivity of the shipped crowns was tested against strawberry crowns produced at Norcal and Lassen Canyon nurseries in Redding, CA (40° 06' N 122° 40'W) as a yield control for fruit production in California (Table 2). The environmental impact of crown production, therefore, was separated from the fruit production environment by using the yield increment over the control. The first two months marketable yield was considered as yield (actually early yield) and the yield data accumulated from 1996 to 2002 was used for modeling.

Impact of Crown harvest date on time to first flower. Strawberry crowns were purchased from Norcal nurseries in Redding, CA. Crowns were planted at three locations in the province of Saskatchewan: Outlook (51° 28' N), Pike Lake (51° 90' N) and La Ronge (55° 9' N) on the June 3rd, May 16th and May 29th respectively of the year 2000. Plants were planted in a Completely Randomized Design (CRD) with four replicates of five plants each with an inter-row spacing of 30 cm and row spacing of 1.5m. The research plots were maintained following the recommended cultural practices for each region with irrigation occurring throughout the season as necessary.

Strawberry crowns were dug out at weekly intervals from September 6th until the 25th of October, 2000. Crowns were trimmed (leaves were removed) and planted into 10-cm pots filled with the medium of SunShine Mix #4. Plants were grown in a controlled greenhouses at 16 hour light and 22°C / 16°C ± 2°C day and night temperatures. Plants were fertilized weekly with a five 500 ppm of N: P: K: 20:20:20. Flowering data was collected weekly.

Accumulated Chilling Units (ACU) and the Impact of chilling hours on time to first flower. Time to first flower was used from crown harvest date trials at three locations (Outlook, Pike Lake, and La Ronge) in 2000. Chilling hours were accumulated from August 15th to a series of harvest dates starting from September 6 to October 25 in one week intervals. Consequently, chilling hour effect on flowering time was modeled by simple accumulation (Model A) from 0 to 8°C or -2 to 15°C and weighted accumulation (Model B) of hours assuming effective chilling temperature range was from 0 to 8°C or from -2 to 15°C. The Model B weighted accumulation system was developed based on other weighted models (Table 3). Accumulated Chilling Units represents the sum of the number of hours at the specified temperature multiplied by the numerical weighting for that temperature range over time.

Fruit Yield model development and assumptions. Commercial fruit yield data from California was used for fruit yield model construction based on 5 Canadian locations producing crowns, listed in Table 1, over 5 or 6 years (from 1996 to 2002) (Table 2). Assumptions for modeling fruit yield were based on the yield responses which varied from year to year under different chilling temperature ranges. That is, it was assumed that maximum fruit yield response occurred at optimal conditions, negative yield response under adverse temperature conditions, and intermediate fruit yield responses at intermediate temperatures for crown production. A weighted

score for each temperature range was based on plant physiological response and the best data fit indicated by P-values and R^2. The fruit yield to chilling response was found to be maximum at 1.1°C and different from vegetative developmental response (Lieten, 2004). Also, effective chilling temperatures were reported from -2 to 8°C and inhibitory effects may exist when temperatures are greater than 25°C (Darnell and Chandler, 2003). Therefore, models were tested based on different assumptions of effective temperature ranges and fruit yield response was weighted according to three models: Model 0 (M0), Model 1 (M1) and Model 2 (M2) (Table 3). Model 0 represented the simple accumulation of hours when temperatures were between 0 to 8°C from August 15th to crown harvest using hourly average air temperatures, as a control model. Model 1 represented the weighted accumulation of hours when the temperature was between -2 to 8°C and negative accumulation when temperature was greater than 15°C. Optimal temperature for fruit yield was between -2 to 2°C and a proportion of the optimum occurred at other temperatures. Model 2 was similar to Model 1, but effective chilling temperature range was from -1 to 15°C and negative accumulation deemed when temperature was lower than -1°C and greater than 25°C. Optimal temperature for fruit yield was 0 to 2°C and a proportion of the optimum was at other temperatures as well. Temperature of Model 2 was weighted as per Table 3. Chilling hour accumulation was counted from August 15th (about 45 days before crown harvest) or September 1st (about 30days before crown harvest) and was compared in M1 and M2.

Table 1. Geographic locations of strawberry crown production in the provinces of Saskatchewan and Alberta, Canada.

Provinces	Location name	Geographic position
Saskatchewan	La Ronge	55° 9' N, 105° 16' W
	Meadow Lake	54° 7' N, 108° 31' W
	Saskatoon	52° 10' N, 106° 43' W
	Outlook	51° 28' N, 107° 3' W
Alberta	Fort Vermillion	58° 22' N, 116° 2' W

Modeling the impact of diurnal temperature difference on fruit yield and flowering time. Weighted accumulation of days with diurnal temperature differences was used as a diurnal temperature difference index. Models assumed the maximum diurnal temperature difference affects yield and flowering time. Assumptions also included the higher the temperature difference, the greater the impact on yield and flowering time. Data were pooled from 1996 to 2003 (excluding 1997) and five locations (Tables 1, 2). The number of locations may be variable in different years. The weighted score based on maximal and minimal temperature distribution was weighted as per Table 3. The daily results were totalled from August 15 to harvest.

Temperature data collection. Temperature data including hourly and daily temperatures all downloaded from Environment Canada: Climate data online (http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html), except at Pike Lake, where temperatures were measured due to unavailable of the online data source. Air temperature

was used for modeling purpose. Models for flowering time (i.e. impact of chilling units on time to first flower, Model A, B series) and impact of chilling units on fruit yield (Model 0, 1 and 2 series) were constructed (Table 3).

Model Testing Under Controlled Environment and Greenhouse Conditions. Keeping the diurnal temperature spread constant, the effect of alternating temperature on flowering and yield was tested under controlled environment and greenhouse conditions. The controlled environment/greenhouse study used crowns dug in Redvers in July, 2005. Crowns were grown in 6" pots and placed under greenhouse conditions (24/18°C), 18 hr photoperiod for 6 weeks prior to placement under temperature treatments. Temperature treatments are outlined in Table 4. Temperatures were changed at a rate of 2°C/hr under a 12 hr photoperiod. Fifteen treatments were applied: five temperature (min/max: -5/19, -3/21, -1/23, +1/25, and +3/27°C) for 15, 30 and 45 days. Twelve plants per treatment were then evaluated for date of flowering and fruit yield over a period of 3 months under greenhouse conditions of 23/18°C, 18 hr photoperiod. Results were put into M0, M1 and M2 models and compared with field results.

Data analysis. SAS (The SAS® System for Windows, V8.2) regression procedure was used for analyzing the relation of yield and accumulative chilling units or diurnal temperature difference index.

Table 2 Summary of marketable strawberry fruit yield over a 9 year period from 1996-2004 and comparison between California-sourced and Saskatchewan-sourced strawberry crowns

Fruit Production Year	**California Location of Fruit Production**	**Source of Crowns**	**Marketable Fruit Yield kg/ha (lbs/acre)**			
			Jan. + Feb.	+/- %	Total	+/- %
1996	Irvine, California (South Coast Research Station)	Norcal, CA	11,480 (10,221)		115,369* (102,718)	
		La Ronge, SK	16,766 (14,927)	+69%	124,974 (111,269)	+11%
1997	Irvine, California (South Coast Research Station)	Norcal, CA	6,422 (5,718)		97,297* (86,627)	
		Saskatoon, SK	7,388 (6,578)	+15%	107,697 (95,887)	+11%
		La Ronge, SK	9,036 (8,045)	+40%	110,937 (98,771)	+14%
1999	Nakama Ranch, Oxnard, CA.	Lassen Canyon, CA	4,724 (4,208)		45,360** (40,409)	
		La Ronge, SK	5,788 (5,157)	+23%	53,386 (47,559)	+18%
2000	Nakama Ranch, Oxnard, CA.	Fall River, CA	8,245 (7,341)		15,724*** (14,000)	
		Ile a la Crosse, SK	7,086 (6,310)	-16%	11,618 (10,344)	-35.3%
		Outlook, SK	7,857 (6,996)	-5%	13,746 (12,239)	-14.4%
		La Ronge, SK	8,207 (7,307)	-0.5%	13,918 (12,392)	-13.0%
	Mandalay Farms, Oxnard, CA	Fall River, CA	6,993 (6,226)		60,995* (54,306)	
		Outlook, SK	8,932 (7,953)	+22%	60,427 (53,800)	-.01%
		La Ronge, SK	6,348 (5,652)	-10%	51,831 (46,147)	-15%
	Ito Farms, Orange County, CA	Lassen Canyon, SK	10,245 (9,121)		28,342*** (25,234)	

		Ile a la Crosse, SK	11,169 (9,945)	+9%	26,519 (23,611)	-6.9%
		Outlook, SK	9,968 (8,875)	-2.8%	25,026 (22,281)	-13.3%
		La Ronge, SK	9,141 (8,138)	-12%	24,865 (22,138)	-14.0%
2001	Nakama Ranch, Oxnard, CA.	Norcal, CA	6,473 (5,763)		13,631*** * (12,136)	
		La Ronge, SK	5,769 (5,136)	- 12.2%	10,442 (9,297)	-23.4%
	Ito Farms, Orange County, CA	Lassen Canyon, CA	7,598 (6,765)		16,517*** (14,706)	
		Meadowlake, SK	9,226 (8,214)	+21.4 %	16,045 (14,286)	-2.9%
		Outlook, SK	6,194 (5,514)	- 22.7%	12,883 (11,471)	-22.0%
		Manning, AB	4,955 (4,411)	- 53.3%	10,901 (9,706)	-34.0%
		Fairview, AB	7,267 (6,470)	-4.6%	13,874 (12,353)	-16.0%
		Fort Vermillion, AB	6,194 (5,514)	- 22.7%	12,223 (10,882)	-26.0%
2002	Ito Farms, Orange County, CA	Lassen Canyon, CA	7,373 (6,564)		35,528*** (31,632)	
		La Ronge, SK	8,227 (7,325)	+11.6 %	22,594 (20,116)	-36.4%
		Meadowlake, SK	9,795 (8,721)	+32.8 %	32,520 (28,953)	-8.5%
		Outlook, SK	8,619 (7,674)	+16.9 %		
		Manning, AB	7,966 (7,093)	+8.0%	27,426 (24,419)	-22.9%
		Fairview, AB	8,489 (7,559)	+15.1 %	26,120 (23,256)	-26.5%
		Fort Vermillion, AB	7,313 (6,512)	-0.8%	27,948 (24,884)	-21.4%
		Carajou, AB	7,314 (6,511)	-0.8%	27,818 (24,767)	-21.4%
2003	Ito Farms, Orange County, CA	♦ Harvested Sept. 8-11, 2002 (see note below)				

2004	Ito Farms, Orange County, CA		Total #baskets / 50 plants		Total #baskets/ 50 plants*** *	
		Lassen Canyon, CA	21.75		56.25	
		Redvers, SK Harvested Sept. 25, 2003	23.75	+0.9%	45.25	19.6%
		Edenwold, SK Harvested Sept. 25, 2003	20.5	-0.9%	35.5	-36.9%
		Canora, SK Harvested Sept. 23, 2003	23.25	+1.1%	40.75	-27.6%
		Nipawin, SK♥ Harvested Sept. 27, 2003	50.0	+130 %	81.0	+44%
		Outlook, SK♥ Harvested Sept. 28, 2003	32.5	+49%	59.75	+6.2%
		Greenhouse plugs, SK	19.75	-0.9%	56.5	+0.04%

+/- represents the percentage above or below California-sourced crowns.
Fruit yield to June 30; **Fruit yield to May 30; ***Fruit yield to April 11; ****Fruit yield to March 31.

♦ In the fall of 2002, all 4 Saskatchewan locations (Edenwold, Nipawin, Rosthern, Outlook) were harvested abnormally early (by September 11). All crowns subsequently died within 6 weeks after planting in California and therefore no fruiting data is available for the 2003 season.

♥ Represents daughter crowns produced in the second year (from overwintered mothers).

Table 3. Summary of Models. temperatures and weighting

Model	Temperatures (°C)	Weighting
A	0 to 8	None (simple accumulation of hours under these temp. from Aug. 15)
	-2 to 15	None (simple accumulation of hours under these temp. from Aug. 15)
B	-2 to < -1	1.0
	-1 to < 0	2.0
	0 to < 2	2.5
	2 to < 5	2.0
	5 to < 8	1.0
	8 to < 15	0.5
M0	0 to 8	None (simple accumulation of hours under these temp. from August 15 – crown harvest)
M1	-2 to 2	1.0
	> 5 to 8	0.4
	> 8 to 15	0.0
	> 15	-1.0
M2	< -1	-1.0
	-1 to 0	0.8
	0 to < 2	1.0
	2 to < 5	0.8
	5 to < 8	0.4
	8 to < 15	0.2
	15 to < 25	0.0
	> 25	-1.0
	> 14 to 16	2.0
	> 12 to 14	1.5
	> 10 to 12	1.0
	> 8 to 10	0.5
	> 6 to 8	0.0
	> 4 to 6	-0.5
	> 2 to 4	-1.0

Table 4. Experimental Results From Chilling Unit Models (M0, M1, and M2) with 15 treatments and 12 plants per treatment

		Min T (°C)	Max T (°C)	Rate/hour *	Treatment duration (days)	Calculated ACU (Accumulated daily Chilling Units) M0	M1	M2
Trt. 1	Chamber 1	-5	19	2	45 days	360	360	225
Trt. 2					30 days	240	240	165
Trt. 3					15 days	120	120	90
Trt. 4	Chamber 2	-3	21	2	45 days	360	360	315
Trt. 5					30 days	240	240	225
Trt. 6					15 days	120	112.5	106.5
Trt. 7	Chamber 3	-1	23	2	45 days	360	315	324
Trt. 8					30 days	240	195	204
Trt. 9					15 days	112.5	90	94.5
Trt. 10	Chamber 4	1	25	2	45 days	315	225	198
Trt. 11					30 days	195	135	117
Trt. 12					15 days	90	61.5	52.5
Trt. 13	Chamber 5	3	27	2	45 days	225	144	27
Trt. 14					30 days	135	84	6
Trt. 15					15 days	60	36	0

* Temperature change rate during 24 hours, 2°C/hour increase in the morning and 2°C/hour decrease in the afternoon
** Constant diurnal day/night temp. shift
*** Flowering time and number, and yield need to be recorded at the same growth conditions after the treatment

Results

Modeling the impact of Accumulative Chilling Units (ACU) on time to first flower. Strawberry plant flowering time varied from 46 to 71 days according to different crown harvest dates and was negatively related to accumulative chilling unit (ACU) (Fig. 1). The more chilling units accumulated during crown development, the shorter the flowering time. Flowering time was significantly ($P<0.01$) related to ACU with both Model A (simple accumulation) and Model B (weighted accumulation) even though these models were based on different chilling unit scales (Table 1). However, the effective temperature range influenced model fit over the weighted score in that when the effective temperature range was extended from 0 to 8°C to a wider range of -2 to 15°C, the regression had the highest R^2 by Model A. Therefore, when modeling chilling unit effect on strawberry flower initiation, one may accumulate under a wider range of temperatures.

Modeling accumulative chilling units on fruit yield and model comparisons. Model 1 was based on accumulated chilling units between -2 to 8°C and the data established the regression relation between fruit yield and ACU when data was analyzed separately by location (Fig. 2). The ACU accumulated from August 15th (about a month and a half before crown harvest) or September 1st (about a month before crown harvest) obtained similar relations in fruit yield and chilling requirement in La Ronge, but not in Outlook. Both locations showed that yield responses to ACU during crown development reached an optimal level (135 ACU for La Ronge and 100 ACU for Outlook). Fruit yield decreased when Accumulated Chilling Units were lower or greater than the optimal ACU. However, the pooled data from five locations (Table 4) over a six year period (1996-2002, except 1998) did not establish a significant regression relationship between yield and ACU by Model 1 (Fig. 4).

Model 2 adjusted the temperature ranges over Model 1 of chilling requirement when the ACU was accumulated from Aug 15th in La Ronge and Outlook (Fig. 3). This model showed that the ACU accumulated from August 15th or September 1st, obtained a different relationship of yield and ACU. Meanwhile, the optimal ACU for maximal yield varied greatly with location, representing about 150°C hr difference between La Ronge and Outlook.

Three models (M0, M1, and M2) for ACU were compared using pooled data from five locations over a six year period (Fig. 4). M0 was based on a simple accumulation of temperature from 0 to 8°C (standard model) and M1 utilized a limited temperature range. Both M0 and M1 models did not obtain significant regressions between yield and ACU. However, M2 was significant and the yield reached its maximum when ACU was about 200 to 250°C hr.

Modeling diurnal temperature difference and its relation to flowering time. A model was developed to accumulate diurnal temperature difference: diurnal temperature difference index . The diurnal temperature difference during crown development affected strawberry flowering time (Fig. 5). Flowering time was shorter with the increase of the index. When the ACU was separately analyzed by each location (data not shown) or pooled data from geographically closer locations (Fig. 5-A), the regression between flowering time and the index was significant and had a higher R^2. When data was pooled from relatively distant locations (i.e. La Ronge vs Outlook and Pike Lake), the regression was not significant and had a lower R^2 (Fig. 5-B). The regressions between flowering time and the index was improved when incorporating the average day length into the index model both in two geographically close locations (Fig. 5-C) and in three distant locations (Fig. 5-D) indicated by p value and R^2 (Fig. 5). The improvement of the regression showed the flowering time was affected by diurnal temperature difference and day length. The time to first flower was more related to the index accumulated from August 1st (two months before crown harvest) than from July 1st (three months before crown harvest) (data not shown).

The R^2 values were 0.63 and 0.36 respectively from July 1st (vs. 0.83 and 0.48 from August 1st) for two close locations and three distant locations, respectively without incorporation of day length.

Modeling diurnal temperature difference and its relation to fruit yield. The greater the diurnal temperature difference, the more fruit yield was positively affected and a linear relation existed between the index and fruit yield (Fig. 6). The linear regression model ($P > 0.01$) well described pooled data from different years and locations, which clearly indicates diurnal temperature differences affect yield and has little interaction with other environmental factors across years and locations. The index accumulated from July 1st (three month before crown harvest, R^2=0.68) had a slightly higher R^2 compared to from August 1st (two months before crown harvest, R^2=0.64), but both were significant at $P = 0.01$.

Model Testing. Consistent with the field study, controlled environment tests confirmed that the simple ACU model (M0) was the most highly correlated with time to flower in that the greater the chilling unit accumulation, the faster the flowering (Fig. 7). But by contrast to previous results under field conditions, M0 was also the most highly correlated with fruit yield and ACU (Fig. 8, Table 5). However, consistent with the field results, an accumulation of 200-250 ACU coincided with the optimum yield response (Fig. 4) and thereafter, yield decreased with increasing chilling unit accumulation (Fig. 8). Runner production decreased with chilling unit accumulation (Fig. 9, Table 6) but it is not known if extending chilling accumulation beyond 400 hrs will begin to increase number of runners.

Discussion

Chilling requirement for flowering and yield. Chilling effects for time to first flower can be modeled by simple accumulation of chilling hours as per the current standard model, although

the effective temperature range can be extended to -2 to +15°C. The relationship of flowering time to chilling hours was not further improved using the model of weighting accumulation of ACU, which was aimed to apply the assumption that different temperatures have unequal effects for promoting flowering in strawberry. By contrast, fruit yield has the weakest relationship with the simple accumulation model (M0) ACU. Thus, temperatures have unequal impact on fruit yield, which may relate to different temperature responses of the balanced growth of vegetative organs and reproduction organs (the yield), carbohydrate reserve and partitioning during crown development. In addition, most temperatures that the plants were exposed to had a positive or a negative impact on yield, which was shown by the best description of yield and ACU using Model 2. Temperatures involved in Model 2 were negative effects on fruit yield when temperature was < -1°C and $\geq$ 25°C, chilling positive effects when temperature was between ≥ -1 and 15°C, and optimal effects was at $\geq 0 \sim < 2$°C.

In conclusion, flowering time can be best described ($R^2 = 0.84$) by a quadratic function of ACU that was modeled by a simple accumulation of chilling hours from -2 to 15°C. The more the chilling hours were accumulated by crowns, the shorter the flowering time. By contrast, the fruit yield was best correlated ($R^2 = 0.80$) with ACU across 5 locations in 6 years periods when the ACU was modeled by a weighted accumulation model, Model 2. The chilling effective range in Model 2 was between -1 to 15°C. Fruit yield was linearly increased with the greater diurnal temperature differences and the flowering time tended to be shorter. However, the diurnal temperature difference affected flowering time interactively with day length among locations.

Model Testing. The time to flowering appears to be very strongly correlated with M0, simple ACU. This was consistent between both field and controlled environment conditions. Thus, the more chilling units accumulated, the faster the flowering. The yield response is more difficult to explain. Unlike the field results, a weighted temperature model of M1 and M2 did not correlate

with yield as well as the simple M0 which only took into account the temperatures between 0 and +8C. It is not known why the weighted model of M2 was less correlated with yield under controlled environment conditions than the simple ACU. When the diurnal temperature shift was kept at a constant difference of 24°C, the highest chilling unit accumulation occurred under the lower range of -5/19, -3/21 and -1/24°C Min./Max. temperatures. Coincidentally, a chilling accumulation of 200 – 250 hr under both field and controlled environment coincided with optimum yield. Chilling accumulation beyond this point began to reduce yield. This reduction does not appear to be associated with competition from runner production.

Day/night temperature shift

The greater diurnal temperature difference at cooler temperature regimes may be the major contributor to the Northern Vigour® response of strawberry crowns produced in Saskatchewan. An accumulative day-night temperature index of 180 resulted in yield enhancements based on Saskatchewan-grown crowns of 30% over California-sourced crowns. Since this response is linear, the day/night temperature differences can be placed into a model and a running total of accumulative day-night temperature indices can be monitored. Since time to first flower is also a linear response with temperature, this aspect of crown quality can also be easily tracked through the simple chilling unit accumulation of M0. Both diurnal temperature and M0 can be easily monitored with inexpensive "Hobo" type thermal data acquisition systems (about $100) placed into the field and downloaded into a computer. A combination of accumulative day-night temperature index and application of a chilling model may most accurately predict fruit yield response and best time to harvest.

Future Research and Suggestions

1. Chilling requirement for flowering initiation and time to first flower can be different from the chilling effects on fruit yield. The yield may depend on the balance growth of vegetation and reproduction and carbohydrate reserve. The chilling model, therefore, cannot only concentrate on flowering time. Yield and yield components have to be involved, such as number of flowers per plant, flower abortion rate, fruit development and yield per plant.

2. Day-night temperature difference may have interactive effects on chilling requirement or *vice versa*. La Ronge data (1995, 1996) have high accumulation of chilling hours and day-night temperature affects little on the yield.

3. Crowns from first year daughter plants or second year daughter plants may have different requirement of chilling. The chilling requirement model should be established separately for them since the plant development conditions are different when they receive the chilling temperatures.

4. This data was based on the 'Camarosa' cultivar. While the trends will likely be consistent between other cultivars, specific quantities of accumulative day-night temperature index to induce enhanced yield may vary and should be evaluated in other cultivars.

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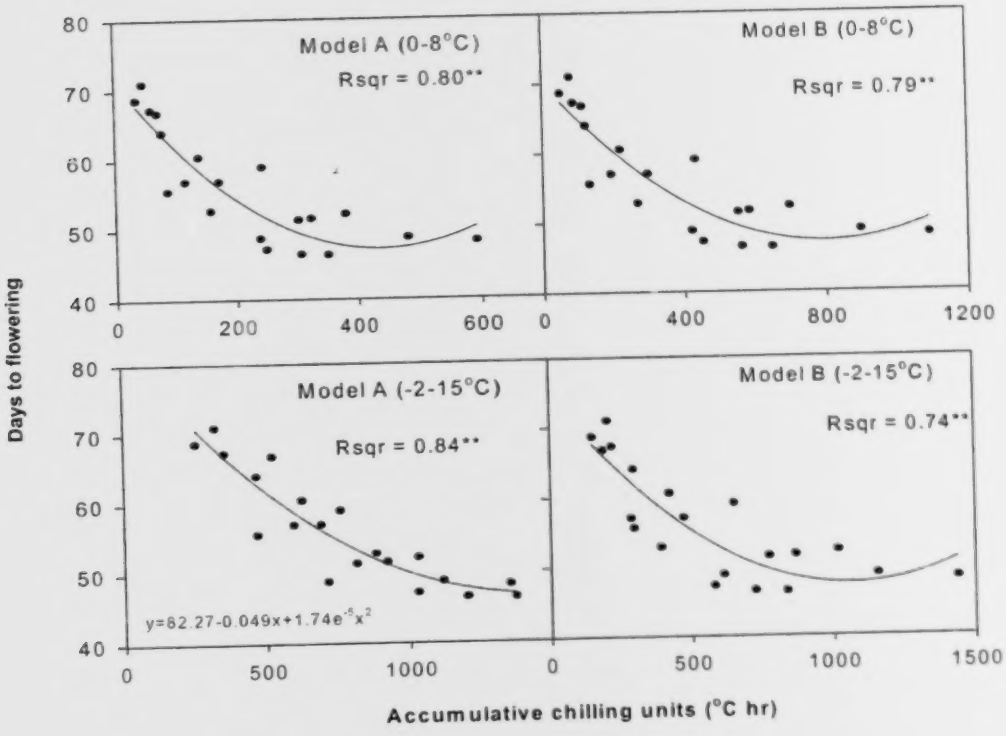

Fig. 1. Modeling flowering time using chilling units accumulated during strawberry crown development. The strawberry crown harvested on various dates from September 6 to October 25, 2000 in weekly intervals and replicated in three growing locations: Outlook (51° 28' N), Pike Lake (51° 90' N) and La Ronge (55° 9' N), Saskatchewan. Model A used chilling hours that simply accumulated from 0 to 8°C or -2 to 15°C; and Model B used chilling hours that weighted accumulation at different temperature ranges from 0 to 8°C or -2 to 15°C, and weighting scores are: ≥ -2 ~ < -1°C:1.0; ≥ -1 ~ < 0°C:2.0; ≥ 0 ~ < 2°C:2.5; ≥ 2 ~ < 5°C: 2.0; ≥ 5 ~ < 8°C: 1.0; and ≥ 8 ~ < 15°C:0.5. Fitted lines are quadratic function. **: P value was significant at 0.01.

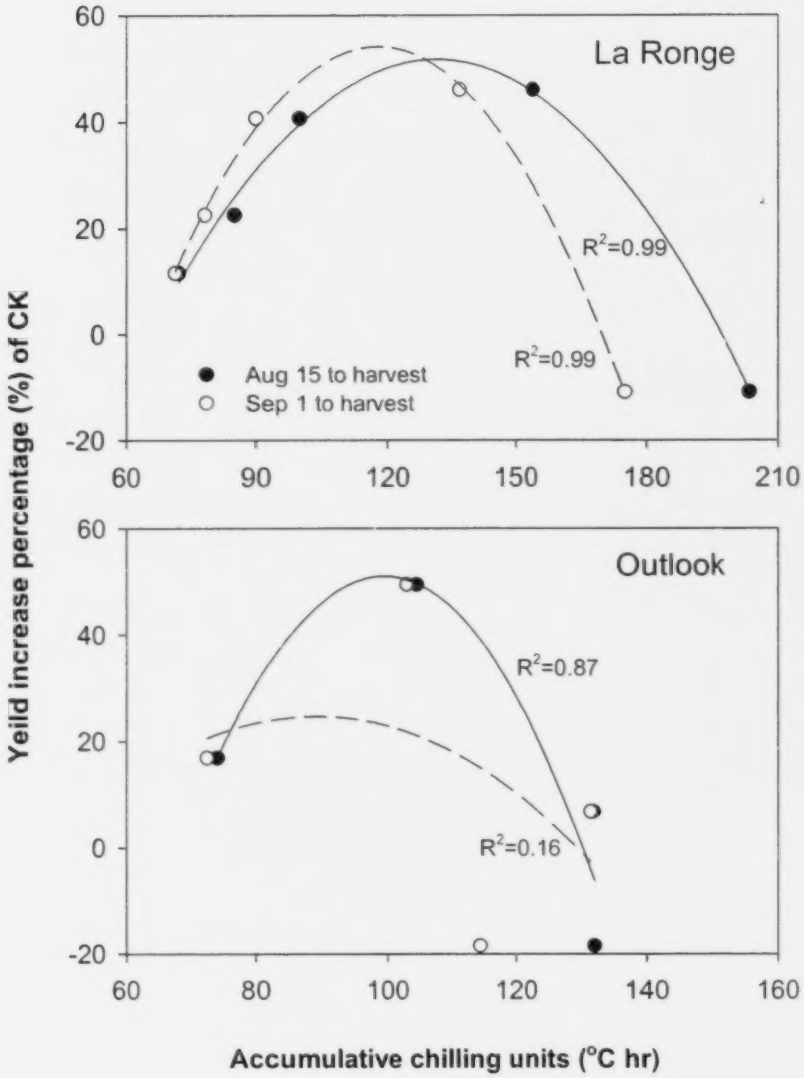

Fig. 2. Modeling yield increment responses to accumulative chilling units during crown production using weighted accumulation from -2 to 8°C with an inhibition effect when temperatures were > 15°C (Model 1). Temperatures were weighted as: ≥ -2 ~ ≤ 2°C: 1; > 2 ~ ≤ 5°C: 0.8; > 5 ~ ≤ 8°C: 0.4; > 8 ~ ≤ 15°C: 0; > 15°C: -1. Fitted lines are a quadratic function.

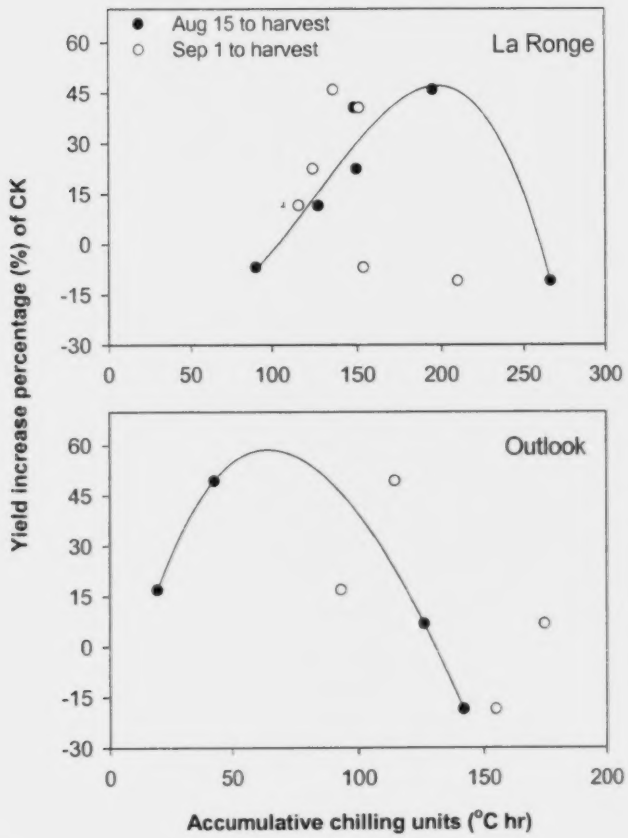

Fig. 3. Modeling yield incremental responses to accumulative chilling units during crown production using weighted accumulation in all temperatures with inhibition effect when temperature < -1°C and ≥ 25°C (Model 2). Temperature weighted as :< -1°C: -1; ≥ -1 ~ < 0°C: 0.8; : ≥ 0 ~ < 2°C: 1; ≥ 2 ~ < 5°C: 0.8; : ≥ 5 ~ < 8°C: 0.4; : ≥ 8 ~ < 15°C: 0.2; ≥ 15 ~ < 25°C: 0; ≥ 25°C: -1. Fitted lines are cubic function.

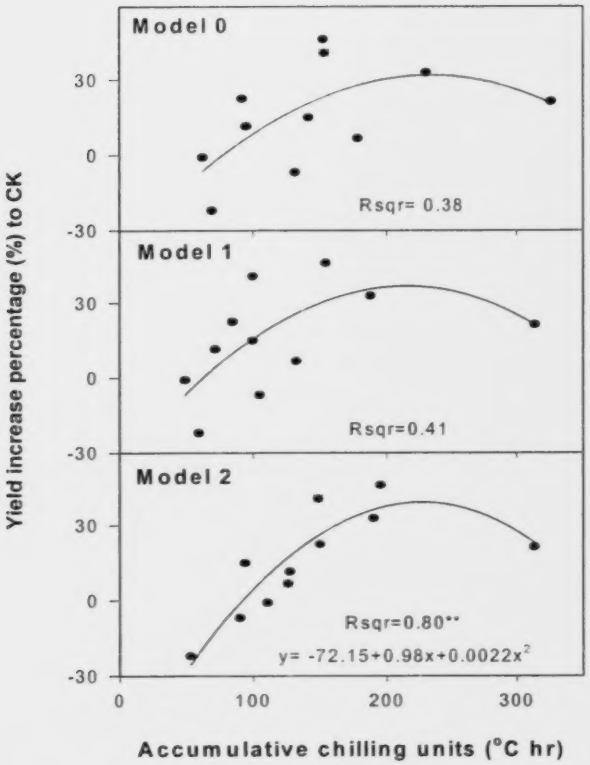

Fig. 4. Model comparisons on yield incremental responses to accumulative chilling units during crown production using Model 0: simple accumulation of chilling units from ≥ 0 to $\leq 8^{\circ}C$, Model 1 and Model 2 with pooled data from 1995 to 2001 (excluding 1997) crown production years and 5 locations (listed in Table 3, the number of locations may be variable in years). Fitted lines are quadratic function. **: P value was significant at 0.01.

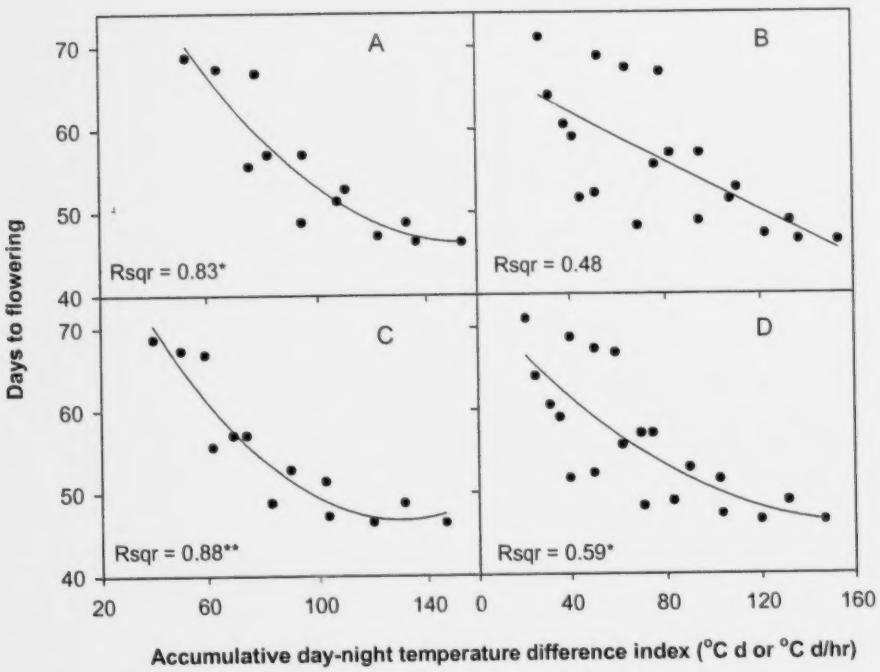

Fig. 5. Modeling flowering time using diurnal temperature difference index and data pooled from different geographic locations. A: pooled data from two geographically close locations (Outlook and Pike Lake) using the index; B: pooled data from three geographically separate locations (Outlook, Pike Lake, and La Ronge) using the index; C: Pooled data from the two locations of A using the index incorporating day length (total accumulation of diurnal temperature difference/day length × 10); D: Pooled data from three locations same as B using the index incorporating day length. Index: weighted accumulation of days with maximal diurnal temperature difference score accumulated from August 1st (two months before crown harvest) during strawberry crown production. Maximal diurnal temperature difference weighting score as: Max-Min temperature > 16°C: 2.5; > 14 ~ ≤ 16°C: 2.0; > 12 ~ ≤ 14°C: 1.5; > 10 ~ ≤ 12°C: 1.0; > 8 ~ ≤ 10°C: 0.5; > 6 ~ ≤ 8°C: 0; > 4 ~ ≤ 6°C: -0.5; > 2 ~ ≤ 4°C: -1.
Fitted lines are a quadratic function. *: P value was significant at 0.05; **: P value was significant at 0.01.

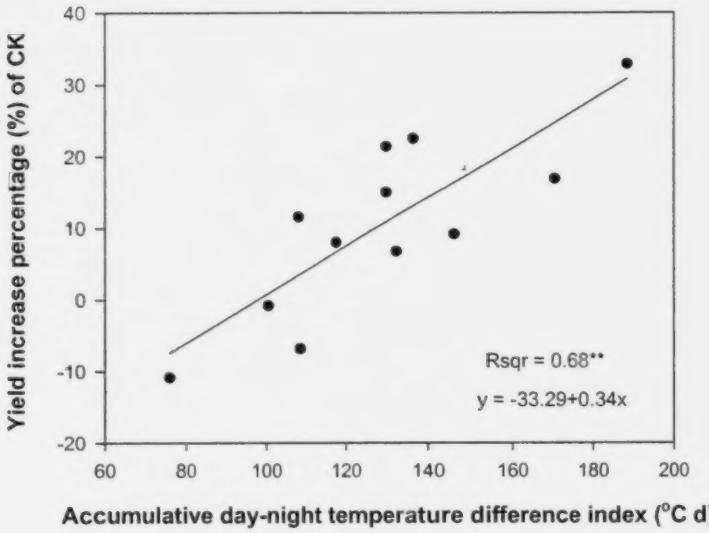

Fig. 6. Modeling yield increase response using diurnal temperature difference index (index: weighted accumulation of days with maximal diurnal temperature difference score) that accumulated during strawberry crown production. Data were pooled from 1996 to 2003 (excluding 1997) and five locations (Table 3). The number of locations may be variable in different years. Maximal diurnal temperature difference weighting score as: Max-Min temperature > 16°C: 2.5; > 14 ~ ≤ 16°C: 2.0; > 12 ~ ≤ 14°C: 1.5; > 10 ~ ≤ 12°C: 1.0; > 8 ~ ≤ 10°C: 0.5; > 6 ~ ≤ 8°C: 0; > 4 ~ ≤ 6°C: -0.5; > 2 ~ ≤ 4°C: -1. **: P value was significant at 0.01.

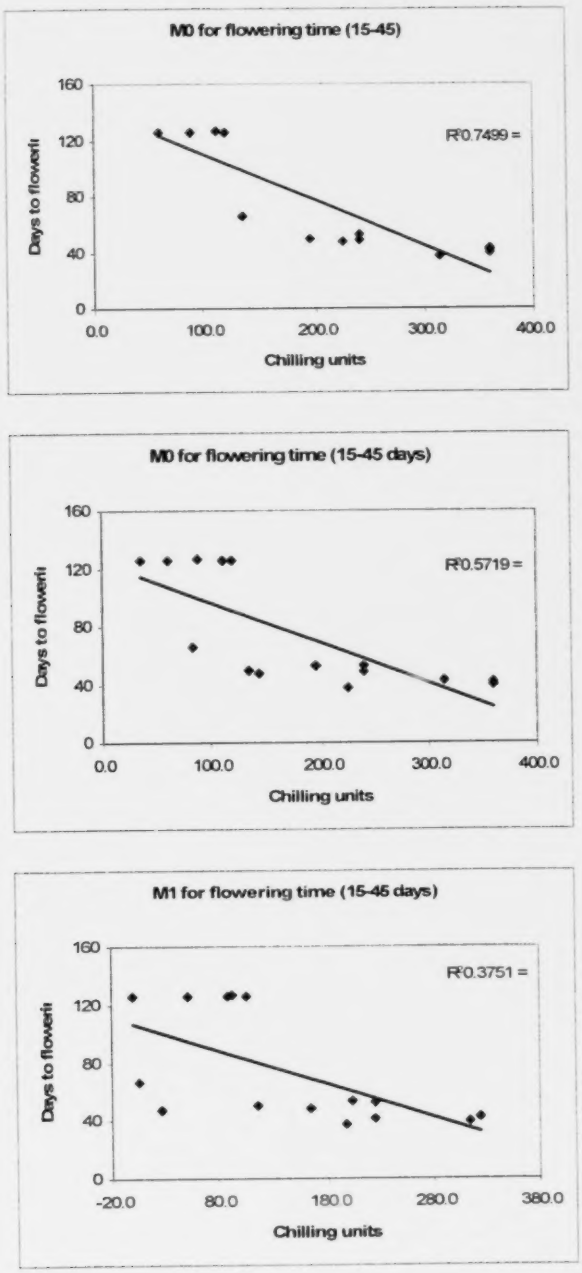

Fig. 7. Days to flowering for all fifteen treatments under greenhouse conditions after exposure to controlled environment treatments for 15, 30 and 45 days with a standard day/night temperature difference of 24°C but shifting min/max temperatures.

Table 5. Fifteen treatments of five temperatures and exposure times of 15, 30 and 45 days under controlled environment conditions. Flowering and yield were subsequently assessed under greenhouse conditions over a 3 month period. Chilling hours were assessed according to three models (M0, M1, M2).

				Chilling hours									
	Min T (C)	Max T (C)	Treatment duration	M0	M1	M2	Flower rate %	Total # flowers	Days to flowering	Number of runners	Yield (g/plant)	Adjusted Yield /plant	Yield /acre
Trt. 1	-5	19	15 days	120.0	120.0	90.0	27.3	1.6	126	2.5			
Trt. 4	-3	21	15 days	120.0	112.5	106.5	75.0	10.0	126	4.1			
Trt. 7	-1	23	15 days	112.5	90.0	94.5	81.8	9.5	127	5.2			
Trt. 10	1	25	15 days	90.0	61.5	52.5	66.7	8.1	126	4.4			
Trt. 13	3	27	15 days	60.0	36.0	0.0	83.3	7.3	126	6.6			
Trt. 2	-5	19	30 days	240	240	165	100.0	13.27	48.4	0.5	74.6	39.1	899.4
Trt. 5	-3	21	30 days	240	240	225	91.7	13.67	52.2	0.9	63.7	40.6	934.5
Trt. 8	-1	23	30 days	240	195	204	83.3	12.33	52.9	0.7	48.6	29.8	685.9
Trt. 11	1	25	30 days	195	135	117	100.0	18.75	50.0	0.7	65.0	43.4	999.2
Trt. 14	3	27	30 days	135	84	6	100.0	15.08	65.9	1.6	42.9	6.6	151.0
Trt. 3	-5	19	45 days	360	360	225	100	13.1	41	0.2	49.25		1132.7
Trt. 6	-3	21	45 days	360	360	315	100	22.8	39	0.4	54.20		1246.5
Trt. 9	-1	23	45 days	360	315	324	100	15.8	42	1.0	46.38		1066.6
Trt. 12	1	25	45 days	315	225	198	100	21.9	37	0.8	82.56		1898.9
Trt. 15	3	27	45 days	225	144	27	100	23.4	48	1.9	73.96		1701.0

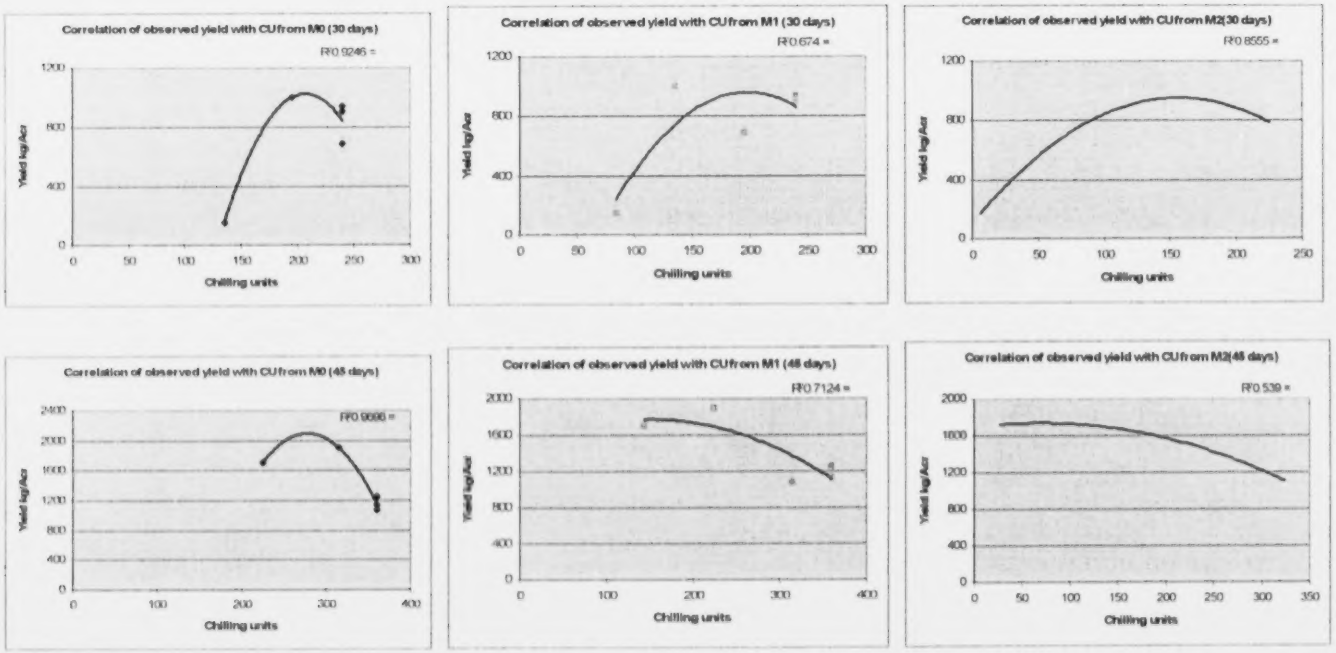

Fig. 8. Correlation of fruit yield and chilling units according to models 0, 1 and 2 as induced under controlled environment and greenhouse conditions.

Table 6. Effect of temperature on runner number, flowering rate and total flower numbers.

Min T (C)	Max T (C)	Rate change /hour	Treatment duration	Chilling hours			Flower rate %	Total # flowers	Number of runners
				M0	M1	M2			
-5	19	2	15 days	120.0	120.0	90.0	27.3	1.6	2.5
-3	21	2	15 days	120.0	112.5	106.5	75.0	10.0	4.1
-1	23	2	15 days	112.5	90.0	94.5	81.8	9.5	5.2
1	25	2	15 days	90.0	61.5	52.5	66.7	8.1	4.4
3	27	2	15 days	60.0	36.0	0.0	83.3	7.3	6.6
1	25	2	30 days	195	135	117	100.0	18.75	0.7
3	27	2	30 days	135	84	6	100.0	15.08	1.6
-5	19	2	45 days	360	360	225	100	13.1	0.2
-3	21	2	45 days	360	360	315	100	22.8	0.4
-1	23	2	45 days	360	315	324	100	15.8	1.0
1	25	2	45 days	315	225	198	100	21.9	0.8
3	27	2	45 days	225	144	27	100	23.4	1.9

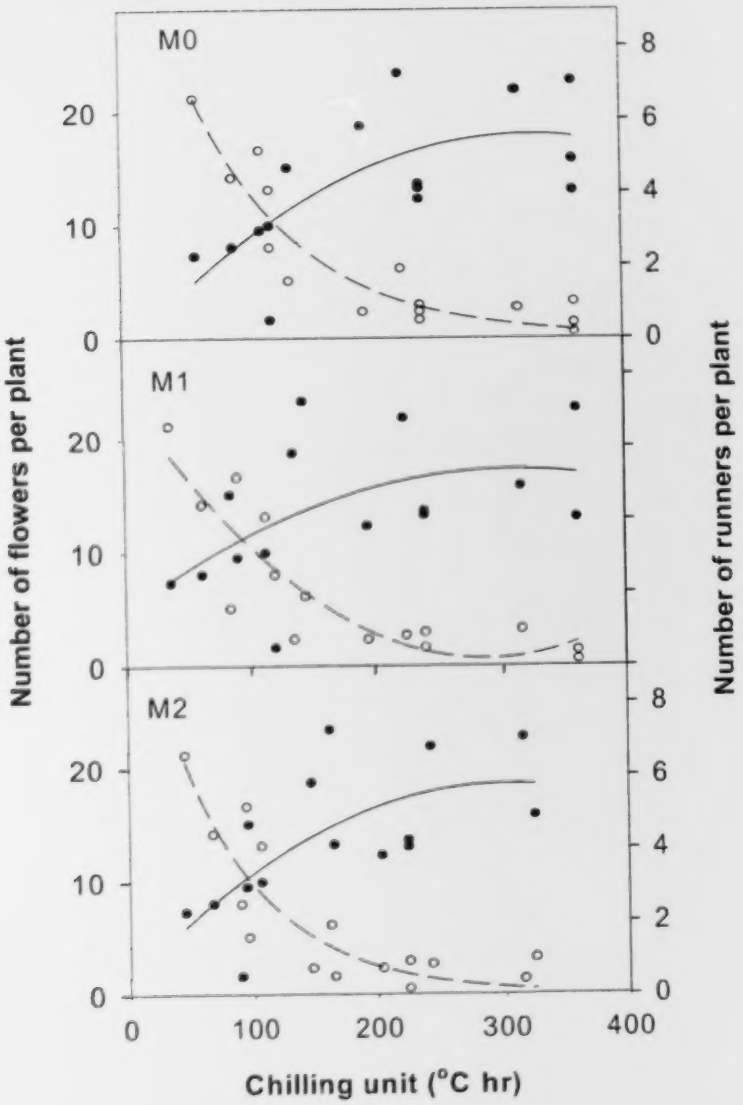

Fig. 9. Correlation of number of flowers (Solid line) and number of runners (dashed line) with chilling units according to M0, M1 and M2 models.